SUMMARY OF HYDROLOGIC AND PHYSICAL PROPERTIES OF ROCK
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REPORT

Summary of Hydrologic and Physical Properties of Rock and Soil Materials, as Analyzed by the Hydrologic Laboratory of the U.S. Geological Survey 1948-60

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By D. A. MORRIS and A. I. JOHNSON

CONTRIBUTIONS TO THE HYDROLOGY OF THE UNITED STATES

UNITED STATES DEPARTMENT OF THE INTERIOR

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GEOLOGICAL SURVEY

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ABSTRACT

The Hydrologic Laboratory was established in 1948 to serve as the central testing laboratory for the Water Resources Division of the U.S. Geological Survey. Since then, thousands of samples of rock and soil materials have been analyzed in the laboratory. Analytical data on samples from 42 States and for the period 1948-60 are summarized in this report.

The data are presented in a form that allows easy comparison of the physical and hydrologic properties of many sedimentary, igneous, and metamorphic rock and soil materials. Sedimentary rocks—the principal water-bearing rocks analyzed—are discussed in detail.

INTRODUCTION

HISTORY AND FUNCTION OF THE HYDROLOGIC LABORATORY

In 1948 the Hydrologic Laboratory of the U.S. Geological Survey was established at Lincoln, Nebr., for the purpose of determining the physical and hydrologic properties of rock and soil materials; A. I. Johnson was its first chief. The laboratory was moved to Denver, Colo., in 1954, and research facilities were expanded. Since that time the field offices of the U.S. Geological Survey in all States have utilized the analytical services and research facilities for many special studies. The laboratory was thus established as a central facility, contributing to the broad objectives of maximum standardization of data and maximum economy of operation and specializing in research on rock and soil properties and analysis.

ANALYTICAL WORK OF THE LABORATORY

Since 1948 the Hydrologic Laboratory has analyzed more than 10,000 samples of rock and soil materials from all States. Standard analyses made by the laboratory are those for permeability, unit
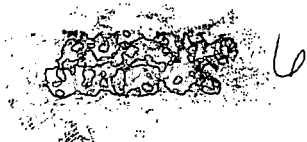
weight, specific gravity, total and effective porosity, centrifuge-moisture equivalent, specific retention, specific yield, Atterberg limits and indices, particle-size distribution (mechanical analysis), moisture content, moisture tension (capillary pressure), degree of saturation, pore-size distribution, carbonate content, soil pH, formation factor, rate and amount of capillarity, gypsum content, acid solubility, soil conductivity, heavy-mineral analysis, and pore-water extraction, among others. The most frequently requested determinations are the first nine just enumerated.

The detailed data concerning any particular analysis, sample, area, or formation are on file at the laboratory. Some of the data have been reported in a variety of publications, and a list through 1965 is provided at the end of this report. The list is not necessarily complete, but it does present those reports that are known to the authors.

PURPOSE AND SCOPE OF REPORT

The purpose of this report is to make the results of laboratory analyses more readily available to field personnel by providing statistical data on the relationship of the hydrologic and physical properties to rock and soil types. The present report is the first of a series in which the hydrologic and physical properties of rock and soil materials are summarized.

For the hydrologic and physical properties of the various rock and soil materials, this report summarizes the range, arithmetic mean, and number of samples represented. Data relative to all the major rock types were not available for the period discussed in this report—1948–60. Many of the data available relate primarily to sedimentary rocks. The extremely diverse types and the large number of data on the physical and hydrologic properties of sedimentary rocks made it imperative to relate these properties to the predominate particle size of the rock. No attempt was made to similarly refine or classify the data for other than sedimentary rocks. In the period 1948–60, samples from 42 States were analyzed.

The method of handling the many data did not allow a correlation between individual samples tested in various ways. For example, some samples were analyzed for both repacked and undisturbed permeability and for repacked and undisturbed porosity. (In this report the term "undisturbed" is applied to any core sample that retains virtually its original structure and placement of particles.) Some of the other samples were analyzed only in undisturbed form or only in repacked form. Accordingly, no direct comparisons of structure and placement of particles can be made for most samples, and each test result should therefore be considered as that derived from a separate sample. However, when both horizontal and vertical permeability

averages are reported, values are given only for those samples on which both tests were used; for such samples, a direct comparison can be made between these two averages.

The samples were considered to be of random origin in regard to location; the sample classifications do not signify either their location or the more detailed effects on them caused by their localized geologic environment. Also, classifications of samples in this report do not include such factors as cementing material, shape of mineral particles, and type of clay mineral. Data for samples known to be poor in quality or nonrepresentative in character, however, have not been included in the summary tables. The data presented are representative of properties of the rock matrix, rather than of the entire rock mass.

DATA STORAGE AND RETRIEVAL SYSTEM

Use of edge-notched data cards, which were designed in 1959, began in 1960 for the recording, filing, and sorting of data used in this report. The unnotched card has two rows of holes inset from its perimeter. Data are coded onto the card by notching the card between a hole and the edge. Thus, when a needle is inserted through one of the holes of a group of notched and unnotched cards, the notched cards fall out and the unnotched remain. Holes made in the margin of the card are identified as to code position, code field, or code section. A code position is a single hole identified by a number, letter, word, or abbreviation of a word. A code field contains more than one code position, and a code section contains more than one code field. Figure 1 illustrates the front side of the edge-notched card designed for this project. On it the code positions are arranged singly, or as code fields or code sections. The code positions are indicated by a single or double row of holes, depending on the space requirements. Most of the code fields are arranged in a linear row, but several are triangular.

One card was used for each sample. In figure 1, the laboratory sample number, 57CAL18, is recorded on the upper left hand corner of the card. The sequence of coding is discussed in a clockwise direction, starting from this point. The first two numerical code sections, separated by the triangular State-code field, indicate the above laboratory sample number. The numerical code system used, called the double-row cipher selective system, requires that all single figures (7, 4, 2, and 1) be notched in the inner row and that all combination figures (3, 5, 6, 8, and 9) be notched in the outer row. The number of ciphers (zeros) are notched in the cipher-code field positioned ahead of the year- or number-code sections. The State abbreviation is dilineated by two converging tiers of State names, selected by two appropriately notched holes. Close observation will indicate two State abbreviations in each rhomb. The State abbreviation closer

FIGURE 1.—Edge-notched data card (sample) used to record results of laboratory analysis.

to the inner part of the card is indicated by the inner row of holes; the State abbreviation closer to the outside of the card is indicated by the outer row of holes. For example, California is coded nearer to the outside of the card; consequently, two notches in the outer row of holes record this location.

Continuing clockwise, a code section indicates particle size. This contains code positions for clay and silt and code fields for sand and gravel. By alining notches in these positions (or fields) with the percentage code, as given by notches along the right margin of the card, the respective particle sizes of the particle-size-distribution graph can be recorded to the nearest 2.5 percent. The reverse side of the card is sensitized, and the graph showing the particle-size distribution may be reproduced on that side of the card by a diazo process (fig. 2).

General hydrologic and geologic properties are coded in the remaining spaces at the bottom of the card. Farther clock-wise and to the left along the lower margin of the card is a code section containing code fields for permeability, specific yield, porosity, and specific gravity. These hydrologic properties can thus be indicated by notches and sorted within these numerical limits. For the triangular code fields along the lower margin of the card, two appropriately notched holes in the outer row of holes indicate the rhomb or category being selected. One notched hole in the inner row of holes indicates the adjacent open rhombohedral or category selected.

At the lower left hand corner of the card is a code section containing triangular code fields for igneous, metamorphic, and sedimentary rocks, and for geologic environment and age. These categories, if properly indicated by notches, allow the relation between geology and hydrologic properties to be compared by sorting. Several direct-sorting code positions (for type of sample) are coded between the geologic triangles in the lower left hand corner of the card. Along the left-hand margin of the card is a code field containing direct-sorting code positions for all the laboratory analyses completed for each sample.

From the previous description, one can see that a much wider variety of data storage, sorting, and correlation techniques is available in the cards as designed than was used for this report. The cards were designed to be as versatile as possible in anticipation of future uses and reports. In more recent years, however, the large number of data has made it necessary to convert to an electronic data-processing system. Punched cards for such a system are now used in the laboratory (Johnson, 1965).
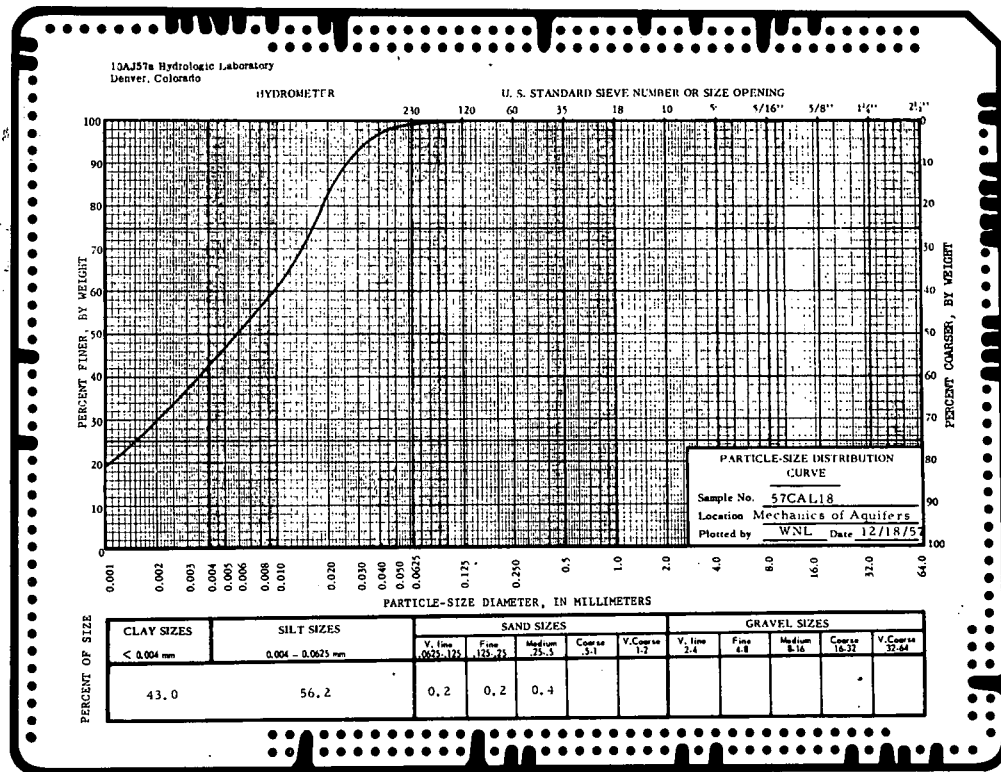
FIGURE 2.—Reverse side of edge-notched data card (sample).

LABORATORY METHODS OF ANALYSIS

Because the primary analytical work at the laboratory has been that of the previously mentioned nine principal tests, only these tests will be compared and discussed in detail in this report. A brief discussion of the laboratory methods for these analyses will follow. Wherever possible, the standard symbols and terminology of the American Society for Testing and Materials (1961) are used. Additional information on theory and methods of analysis can be obtained by referring to publications by Meinzer (1923, 1949), Krumbein and Pettijohn (1938), Wenzel (1942), Taylor (1948), and the American Society for Testing Materials (1964).

PERMEABILITY

Permeability is a measure of the capacity of a material to transmit water under pressure. It can be determined in the laboratory by observing the rate of percolation of water through a sample of known length and cross-sectional area under a known difference in head.

The basic law for flow of fluids through porous materials was established by Darcy, who demonstrated experimentally that the rate of flow of water is proportional to the hydraulic gradient. Darcy's law can be expressed as:

$$Q = kiA,$$

in which

Q = quantity of water discharged in a unit of time,
A = total cross-sectional area through which the water percolates,
i = hydraulic gradient (the difference in head, h, divided by the length of flow, L), and
k = coefficient of permeability of the material for water, or

$$k = \frac{Q}{iA}, \text{ or } \frac{QL}{hA}.$$

The coefficient of permeability, P, used by the Water Resources Division of the Geological Survey is defined (Wenzel, 1942, p. 7) as the rate of flow of water, in gallons per day, through a cross-sectional area of 1 square foot under a hydraulic gradient of 1 foot per foot at a temperature of 60°F. Because relatively pure water is assumed, density is disregarded.

Coefficients of permeability are determined in the laboratory in constant-head or variable-head permeameters (fig. 3). The constant-head permeameter is generally used for samples of medium to high permeability, and the variable-head permeameter, for samples of low permeability.
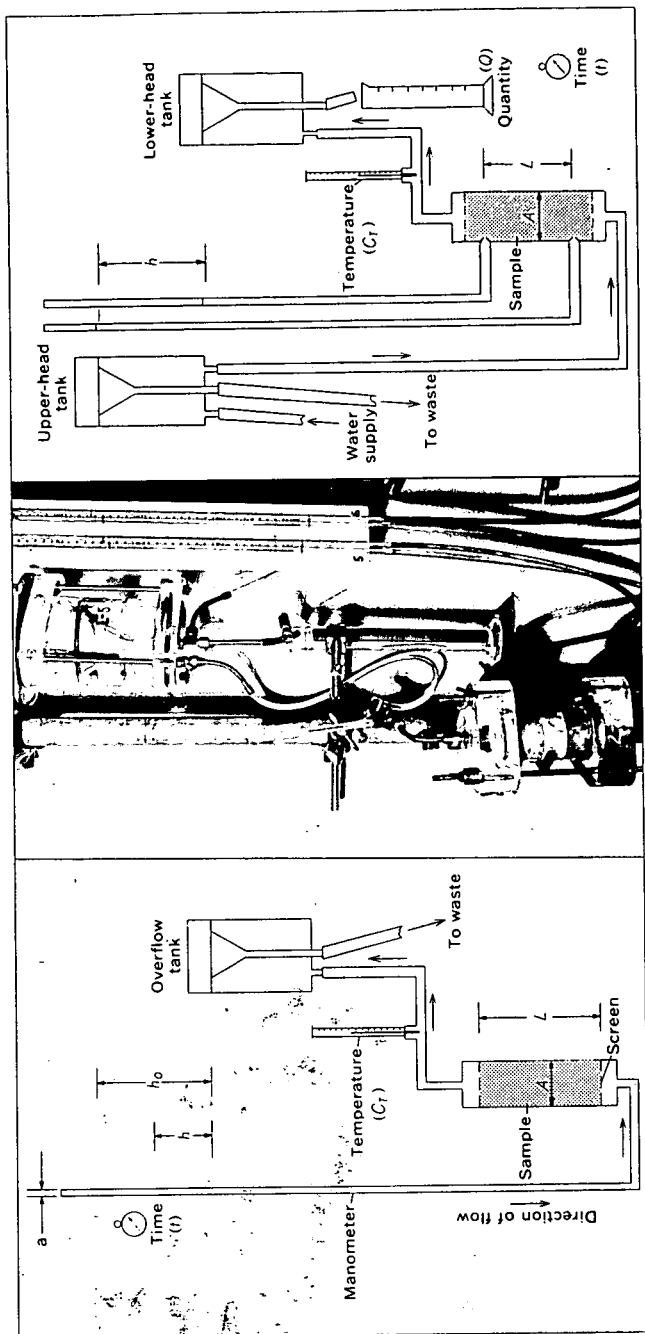
FIGURE 3.—Permeability apparatus. Left, diagram of variable-head type, where $k=2.3\dfrac{aL}{At}\log\dfrac{h_0}{h}\,C_T$. Center, photograph of apparatus. Right, diagram of constant-head type, where $k=\dfrac{QL}{Ath}\,C_T$.

The constant-head method requires observations on the rate of discharge of water through a sample where the difference in head of water at the top and bottom of the sample is maintained at a constant value. From Darcy's law, the basic formula for the constant-head permeameter is

$$k = \frac{QL}{Ath} C_T,$$

where

k = coefficient of permeability,
Q = volume of percolation,
L = length of sample,
A = area of sample cylinder,
t = length of time of flow,
h = difference in head at the top and bottom of sample, and
C_T = ratio of viscosity of water at observed temperature to viscosity at 60°F.

By substituting the units used by the Water Resources Division, the above formula becomes

$$P = \frac{21,200QL}{Ath} C_T,$$

in which P is in gallons per day per square foot, Q is in cubic centimeters, L and h are in centimeters, A is in square centimeters, t is in seconds, and C is dimensionless.

The variable-head method requires that measurement of the quantity of water percolating through the sample be made indirectly by observing the rate of fall of the water level in a manometer connected to the sample. By integrating Darcy's equation, the basic formula for use of the variable-head permeameter is

$$k = 2.3 \frac{aL}{At} \log \frac{h_0}{h} C_T,$$

where

k = coefficient of permeability,
h_0 = head in manometer at zero time,
h = head at any given elapsed time,
t = elapsed time,
A = area of sample cylinder,
a = area of manometer,
L = length of sample, and
C_T = temperature correction.

By substituting the units used by the Water Resources Division, the above formula becomes

$$P = 48,815 \frac{aL}{At} \log \frac{h_0}{h} C_T, .$$

in which P is in gallons per day per square foot, A and a are in square centimeters, L is in centimeters, t is in seconds, h_0 and h are in centimeters, and C_T is dimensionless.

Entrapped air in a sample may cause considerable plugging of pore space and thus reduce the apparent coefficient of permeability. A specially designed vacuum system is therefore used by the laboratory to provide the deaired tap water used as the percolation fluid. The reported coefficient of permeability is the maximum obtained after several test runs and represents the saturation permeability. Chemical analysis of Denver tap water is given in table 1.

TABLE 1.—*Chemical analysis of Denver tap water*

[Results in parts per million except as indicated. Analysis by B. P. Robinson, Quality of Water Laboratory, U.S. Geol. Survey, Denver, Colo.]

Calcium (Ca)	20	Fluoride (F)	0.2
Magnesium (Mg)	4	Nitrate (NO₃)	.6
Sodium (Na) + potassium (K)	3.4	Dissolved solids	99
Sulfate (SO₄)	31	Hardness (CaCO₃)	66
Chloride (Cl)	1.5	Specific conductance (micromhos at 25°C)	161
Bicarbonate (HCO₃)	47	pH	7.3

Undisturbed cores of unconsolidated materials are retained in the cylinder liners of drive-core barrels. Undisturbed cores of consolidated materials are sealed with sealing wax in the percolation cylinders. Disturbed samples of unconsolidated materials are packed in the percolation cylinders by means of a specially designed packing machine (fig. 4) and are referred to in this report as repacked samples. All cylinders are installed directly in the permeameter to serve as the percolation cylinder of the apparatus.

DRY UNIT WEIGHT

The dry unit weight is the weight of solids per unit of total volume of rock or soil mass. It is generally reported in grams per cubic centimeter or in pounds per cubic foot. The dry unit weight decreases with an increase in amount of void space. The dry unit weight divided by the unit weight of distilled water at a stated temperature (generally 4°C) is known as the apparent specific gravity, which is dimensionless.

The volume of the sample is obtained by determining sample dimensions or by mercury displacement. The volume and the oven-dry
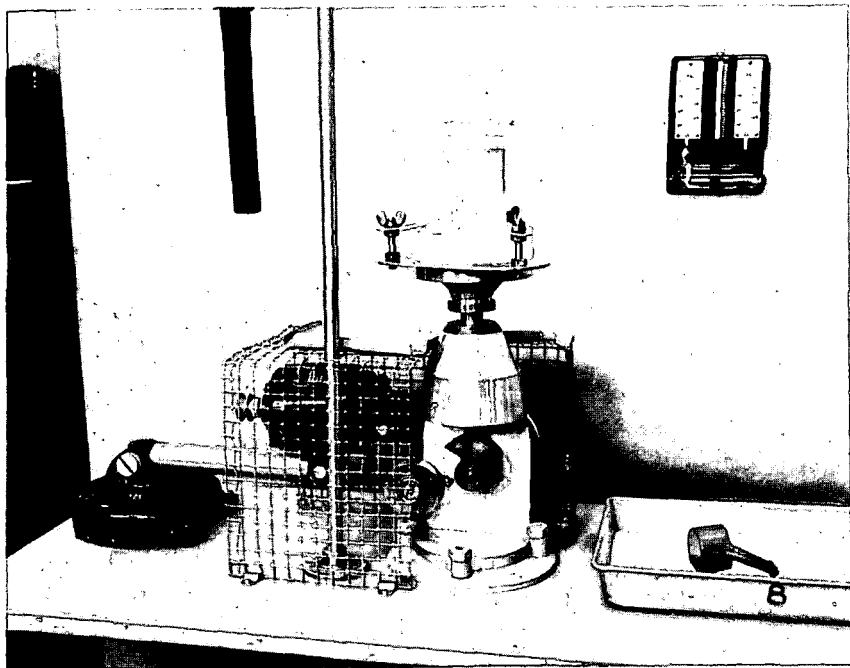
FIGURE 4.—Machine for packing disturbed samples being prepared for permeability or porosity analyses.

weight of this known volume are then used to calculate the dry unit weight as follows:

$$\gamma_d = \frac{W_s}{V},$$

where

γ_d = dry unit weight, in grams per cubic centimeter,
W_s = weight of oven-dry sample, in grams, and
V = total volume of mass sample, in cubic centimeters.

The dry unit weight, in grams per cubic centimeter, is multiplied by 62.4 to convert to pounds per cubic foot.

SPECIFIC GRAVITY OF SOLIDS

The specific gravity of solids, G_s, is the ratio of (1) the weight in air of a given volume of solids at a stated temperature (unit weight of the solid particles or particle density) to (2) the weight in air of an equal volume of distilled water at a stated temperature, generally 4°C.

The volumetric-flask method is used for determining the specific gravity of solids. A weighed oven-dry portion of the sample is dispersed in water in a calibrated volumetric flask. The volume of the particles is equivalent to the weight of displaced water. The unit

weight of the solid particles is obtained by dividing the dry weight of the sample by the volume of the solid particles. Because the density of water at 4°C equals unity in the metric system, the specific gravity of solids is numerically equivalent to this unit weight.

POROSITY

Porosity is defined as the ratio of (1) the volume of the void spaces to (2) the total volume of the rock or soil mass. It is usually expressed as a percentage. Therefore,

$$n = \frac{V_v(100)}{V} = \frac{(V - V_s)(100)}{V},$$

then as

$$\gamma_d = \frac{W_s}{V},$$

and

$$\gamma_s = \frac{W_s}{V_s},$$

$$n = \frac{W_s/\gamma_d - W_s/\gamma_s}{W_s/\gamma_d} \ (100),$$

or

$$n = \frac{\gamma_s - \gamma_d}{\gamma_s} \ (100),$$

where
 $n =$ porosity, in percent,
 $V_v =$ volume of voids,
 $V =$ total mass volume,
 $W_s =$ weight of oven-dry particles,
 $\gamma_s =$ unit weight of solid particles (equal numerically to specific gravity of solids in metric system),
 $\gamma_d =$ dry unit weight of sample, and
 $V_s =$ volume of solid particles.

After the dry unit weight and the unit weight of solid particles have been determined for the sample, the porosity is calculated using the above equation. The relation between these three properties is illustrated in figure 5.

CENTRIFUGE-MOISTURE EQUIVALENT, SPECIFIC RETENTION, AND SPECIFIC YIELD

The centrifuge-moisture equivalent of a rock is the amount of water, expressed as a percentage of the dry weight, retained by the material which has been first saturated with water and then subjected to a force equal to 1,000 times the force of gravity for 1 hour. The centrifuge-moisture equivalent is multiplied by the dry unit weight
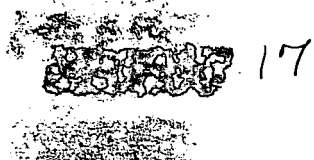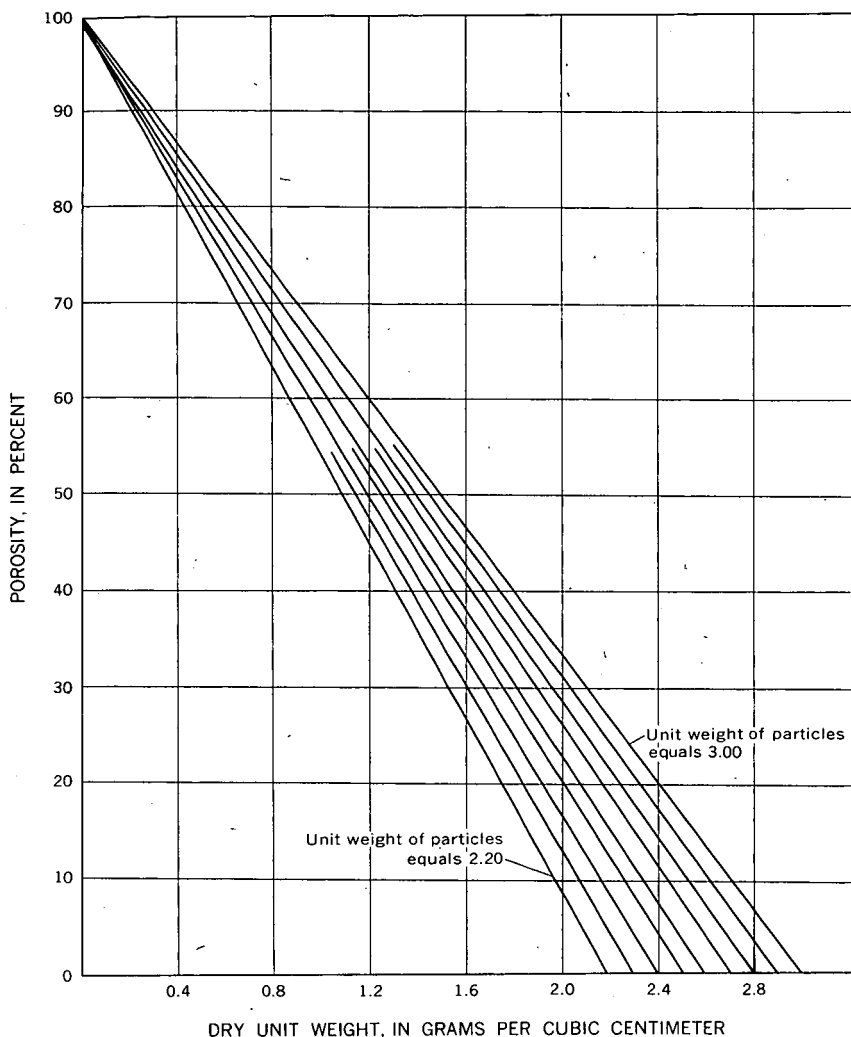
FIGURE 5.—Relation of porosity to dry unit weight for various unit weights of solid particles.

(apparent specific gravity) to obtain the moisture equivalent by volume. Since 1959 these analyses have been made at a constant temperature of 20°C. (See Prill and Johnson, 1960.)

The specific retention of a rock is the percentage of its total volume occupied by water that cannot be drained by gravity and that will not be yielded to wells.

The specific yield of a rock is the percentage of its total volume occupied by water that will drain under gravity to wells. The specific yield of a rock is equal to its porosity minus its specific retention.

The centrifuge moisture equivalent, by volume, is determined and is then adjusted by a correction factor proposed by Piper (1933). This adjusted value, considered to be specific retention, is then subtracted from the porosity to obtain the specific yield.   The centrifuge test is made on undisturbed samples for consolidated rocks and on repacked samples for unconsolidated rocks.

PARTICLE-SIZE DISTRIBUTION

A particle-size analysis, also termed a "mechanical analysis," is the determination of the distribution of particle sizes in a sample.   Particle sizes smaller than 0.0625 mm (millimeter) are determined by the hydrometer method of sedimentation analysis, and sizes larger than 0.0625 mm are determined by wet-sieve analysis.

Samples are prepared for analysis, after being air dried, by gently but thoroughly separating the lumps of material into individual particles by use of a mortar and rubber-covered pestle.   Care is taken to prevent crushing of the individual particles.

The hydrometer method of sedimentation analysis consists of (1) dispersing a representative part of the prepared sample with sodium hexametaphosphate in 1 liter of water, and (2) measuring the density of the suspension at increasing intervals of time with a soil hydrometer.   At given times, the size of the largest particles remaining in suspension at the level of the hydrometer is computed by Stokes' Law (Am. Soc. Testing Materials, 1964, p. 104), and the weight of particles finer than that size is computed from the density of the suspension at the same level.

After the completion of the hydrometer analysis, the sample suspension is poured into a sieve that has openings of 0.0625 mm.   The sample is then gently agitated and washed over the sieve.   The material retained is dried and placed in a set of standard 8-inch sieves, which are shaken for 15 minutes on a Ro-Tap mechanical shaker. The fraction of the sample remaining on each sieve is weighed.

From the hydrometer analysis and the sieve analysis, the percentage of the particles smaller than a given size is calculated and plotted as a cumulative-distribution curve.   The particle sizes, in millimeters, are plotted as abscissas on a logarithmic scale, and the cumulative percentages of particles smaller than the size shown, by weight, are plotted as ordinates on an arithmetic scale.   The percentage in each of several size ranges is then determined from this curve.

The analyses are divided into the following groups according to their particle-size distribution.

Particle-size description	Range of particle diameter (mm)	Particle-size description	Range of particle diameter (mm)
Very coarse gravel	32. 0–64. 0	Coarse sand	0. 5 – 1. 0
Coarse gravel	16. 0–32. 0	Medium sand	. 25 – . 5
Medium gravel	8. 0–16. 0	Fine sand	. 125 – . 25
Fine gravel	4. 0– 8. 0	Very fine sand	. 0625– . 125
Very fine gravel	2. 0– 4. 0	Silt	. 004 – . 062
Very coarse sand	1. 0– 2. 0	Clay	<– . 0045

This classification system is used officially by the Ground Water Branch, U.S. Geological Survey, and is similar to that proposed by the National Research Council (1947). Subsequent references to sand, silt, and clay in this report will relate to sand-, silt-, and clay-size particles as specified in the preceding table.

HYDROLOGIC AND PHYSICAL PROPERTIES OF ROCK AND SOIL MATERIALS

The outer crust of the earth is composed of rock material, which, though not exposed in some places, everywhere underlies the thin mantle of soil, vegetation, or water. This naturally formed mineral matter, whether or not coherent or consolidated, has a certain constancy of chemical and mineral composition for any particular type of material and is therefore considered geologically to be rock.

Rocks can be divided readily according to their mode of origin into three principal groups. These groups are the igneous rocks, formed by the solidification of molten material derived from great depths below the surface; the sedimentary or bedded rocks, formed by the accumulation of sediments in water, from air (eolian), or by gravity; and the metamorphic rocks, formed from igneous or sedimentary rocks that have undergone chemical and physical change by agencies of heat and pressure subsequent to their original formation.

Igneous, sedimentary, and metamorphic rocks differ in mineral composition, texture, and structure, with a consequent difference in number, size, shape, and arrangement of the interstices. Pronounced differences in both physical properties and water-bearing characteristics result. The following discussion will thus be directed toward the analyses the laboratory has made of representative samples of the three classes of rocks and the comparison of their properties.

IGNEOUS ROCKS

Igneous rocks can be divided into three classifications—according to origin, texture, and composition. Each classification has some significance in reference to physical properties and the occurrence of ground water. Only three types of rock of igneous origin have been analyzed in the laboratory—granite, gabbro, and basalt.

Granite, Gabbro and Basalt.—Granite is a light-colored granular rock composed primarily of feldspar and quartz. It generally contains more than one kind of feldspar and takes its color from the predominant one, which is generally orthoclase. Quartz fills the interstices between the other minerals. Gabbro is also granular but consists chiefly of ferro-magnesian minerals, as well as some plagioclase feldspar. Typically, gabbro is dark. Only weathered granite and gabbro samples have been tested in the Hydrologic Laboratory. Basalt is a fine-textured aphanitic rock [1] of very dark color. The rock fabric is so fine that it cannot be perceived even with a lens, and the rock is ordinarily of dull luster. (See table 2 for a summary of the physical and hydrologic data for weathered granite, weathered gabbro, and basalt.)

TABLE 2.—*Properties of weathered granite, weathered gabbro, and basalt*

Test	Granite (weathered)			Gabbro (weathered)			Basalt		
	Range	Arithmetic mean	Number of analyses	Range	Arithmetic mean	Number of analyses	Range	Arithmetic mean	Number of analyses
Permeability, vertical (gpd per sq ft)	7 –110	35	7	1 – 8	4	4	0.00004– 0.9	0.2	93
Dry unit weight (g per cc)	1.21– 1.78	1.50	8	1.67– 1.77	1.73	4	1.99 – 2.89	2.53	94
Specific gravity of solids	2.70– 2.84	2.74	8	2.95– 3.09	3.02	5	2.95 – 3.15	3.07	94
Porosity, undisturbed (percent)	34.3 – 56.6	45	8	41.7 –45.0	43	4	3.0 –35.0	17	94

Water-Bearing Properties of Igneous Rocks.—The water-bearing properties of granite, gabbro, and basalt depend to some extent on their class. Coarse crystalline rocks such as granite and gabbro are usually poor water bearers, especially at depth. Water occurs near the surface in the interstices of the weathered rock or in the joints that extend to greater depth. In much granite, horizontal joint systems increase the water-bearing capacity of the rock. The data for granite and gabbro indicate permeabilities that might be expected from weathered rocks near the surface.

The laboratory tests, in general, reflect the low permeability of the rock matrix but not the influence of joints or weathering on the water-bearing properties of these rocks. This is especially true of the finer textured igneous rocks, such as basalt. Although the data indicate a low permeability and porosity for the basalt analyzed, basalt ranks as one of the major water-bearing rocks of the United States. The

[1] For definition of this and any subsequent terminology used in this report, refer to Rice, 1954; Stokes and Varnes, 1955; or Am. Geol. Inst., 1960.

water occurs in large tubelike cavities and in other cavities in the basalt and in the interflow zone between successive lava sheets.

SEDIMENTARY ROCKS

Sedimentary rocks may be grouped, according to origin, into three classes: clastic deposits of mechanical origin, chemical deposits, and organic deposits. Water occurs primarily in clastic rocks; consequently, most of the analyses are of these rocks.

Deposits of clastic rock are composed of fragments mechanically derived from older rocks during weathering and from their erosion. Such deposits include beds of clay, silt, sand, and gravel, and various mixtures of these materials (both unconsolidated and consolidated), which are laid down in water. Deposits transported by gravity, wind, and ice are also included under this heading, largely for convenience. These deposits are, in general, closely related to stratified rocks and are considered here to be in that category. However, in some publications, gravity, wind, and ice deposits have been described according to their close relation to other rock types.

Chemical deposits consist of substances precipitated out of solution in water. The organic deposits are composed chiefly of the calcareous and carbonaceous remains of animals and plants.

MECHANICAL ORIGIN

Exposure of any type of rock to the action of the atmosphere causes it to gradually disintegrate into soil material. A variety of agencies are involved. All rock masses are penetrated by joints or planes of cleavage. Freeze-and-thaw action of water within these cracks and fissures causes the rocks to crumble and reduces them to debris. The expansion and contraction of rocks in areas of wide temperature range and the effect of many other weathering processes cause the same action, but at a much slower rate. All these processes result in rock materials being broken up by mechanical means into smaller and smaller fragments.

WATER-LAID DEPOSITS

Water-laid deposits include sediments that are derived by disintegration of older rocks and are subsequently laid down in stratified form by water currents in seas and lakes and on the flood plains of rivers. With time, they generally become indurated or consolidated.

Conglomerate and breccia.—Conglomerate is a consolidated clastic rock composed of rounded particles of various sizes, cemented together by another mineral substance. Breccia is similar but consists of sharp angular rock fragments cemented together by mineral

material.   Generally the interstices in conglomerate and breccia are completely filled with cement, and the rocks are generally poor transmitters of water.   Samples of these rocks were not analyzed during the period discussed in this report.

Sandstone.—Sandstone is a consolidated clastic rock composed, usually, of rounded quartz grains (of sand size) that are held together by various cementing substances.   Sandstone is one of the principal water bearers.   It has such a wide range in particle size that samples in the following summary (table 3) have been classified into fine- and medium-grained groups, according to the primary particle size. Although some sandstone beds originated as wind-laid deposits, most of them are water laid; all sandstone is therefore discussed in the section titled "Water-Laid Deposits of Mechanical Origin."

Siltstone, claystone, and shale.—Siltstone, claystone, and shale are very fine grained consolidated clastic rocks composed mainly of silt- and clay-size particles.   Siltstone is composed mostly of silt-size particles, and claystone, of clay-size particles; siltstone and claystone are massive.   Shale is also composed mostly of clay-size particles, but it is thinly laminated.   Table 4 summarizes the properties of these rocks.

Gravel, sand, silt, and clay.—Gravel, sand, silt, and clay are the unconsolidated detrital equivalents of the previously described consolidated sediments.   For the gravel and sand, data have been

TABLE 3.—*Properties of sandstone*

[Classified by predominant particle size]

Test	Fine grained			Medium grained		
	Range	Arithmetic mean	Number of analyses	Range	Arithmetic mean	Number of analyses
Permeability, vertical (gpd per sq ft)_____	0. 008–37	5	20	0. 05–220	77	13
Permeability, horizontal (gpd per sq ft)_____	. 01 –48	7	20	_____	_____	_____
Dry unit weight (g per cc)_____	1. 34 – 2. 32	1. 76	60	1. 50–186	1. 68	10
Specific gravity of solids_____	2. 56 – 2. 72	2. 65	55	2. 64– 2. 69	2. 66	9
Porosity, undisturbed (percent)__	13. 7 –49. 3	33	55	29. 7 – 43. 6	37	10
Centrifuge-moisture equivalent (percent)_____	. 2 –18. 5	6	47	. 3 – 9. 1	4	10
Specific retention (percent)_____	1. 2 –30. 8	13	47	5. 2 – 19. 2	10	10
Specific yield (percent)_____	2. 1 –39. 6	21	. 47	11. 9 – 41. 1	27	10

TABLE 4.—*Properties of siltstone, claystone, and shale*

Test	Siltstone			Claystone			Shale		
	Range	Arithmetic mean	Number of analyses	Range	Arithmetic mean	Number of analyses	Range	Arithmetic mean	Number of analyses
Permeability, vertical (gpd per sq ft)	0.00002– 0.03	0.004	8	0.002	0.002	2	---------	-------	-----
Dry unit weight (g per cc)	1.35 – 2.12	1.61	18	1.37 – 1.60	1.51	4	2.20–2.72	2.53	20
Specific gravity of solids	2.52 – 2.89	2.65	27	2.50 – 2.76	2.66	4	2.47–2.83	2.69	20
Porosity, undisturbed (percent)	21.2 –41.0	35	7	41.2 –45.2	43	4	1.4 –9.7	6	20
Porosity, repacked (percent)	28.8 –47.8	43	11						
Centrifuge-moisture equivalent (percent)	.9 –39.4	14	16						
Specific retention (percent)	5.4 –44.8	29	15						
Specific yield (percent)	.9 –32.7	12	13						

grouped according to predominant particle size into "fine" (very fine and fine classifications), "medium" and "coarse" (coarse and very coarse classifications) ranges. Tables 5 and 6 summarize the properties of these sediments, and figures 6–8 provide typical data on hydrologic and physical properties, as related to particle-size distribution.

Water-bearing properties of water-laid deposits.—Gravel has long been considered to be the best water-laid deposit for yielding water. A clean gravel has high permeability, high porosity, and high specific yield. Most gravel, however, is not clean but contains much fine material, which fills the interstices and decreases the water-yielding properties of the gravel. Also, the laboratory data indicate that the decrease in water-yielding properties takes place principally in gravel that is coarser than the medium-size classification. The presence of fine cementing material in consolidated gravel also alters its hydrologic and physical properties, and in some conglomerate the matrix is so dense that the rock yields little water.

Sand and sandstone also are good producers of water. Sand generally has a higher porosity than gravel because gravel is normally more heterogeneous, but sand will have a porosity comparable to that of gravel having the same degree of assortment and uniformity of grains. Although the interstices in sand deposits are small, those in gravel may even be smaller on the average, and the specific yield of sand is in many places more than that of gravel. The laboratory data substantiate this relation for sand and also indicate that permeability increases as particle size increases. Sandstone, however, has a considerably lower range in hydrologic and physical properties than does sand, owing to size of particles, degree of assortment, degree of cementation, and the resulting decrease in size of interstices. In this

TABLE 5.—*Properties of sand and gravel*

[Classified by predominant particle size]

Test	Fine			Medium			Coarse		
	Range	Arithmetic mean	Number of analyses	Range	Arithmetic mean	Number of analyses	Range	Arithmetic mean	Number of analyses
Sand									
Permeability, repacked (gpd per sq ft)	0.4 – 400	61	159	2.0 – 1,200	300	255	2.0 –14,000	1,100	158
Permeability, vertical (gpd per sq ft)	.1 – 980	94	164	1 – 1,900	340	112	18.0 – 1,900	680	20
Dry unit weight (g per cc)	1.13– 1.99	1.55	374	1.27– 1.93	1.69	341	1.42– 1.94	1.73	158
Specific gravity of solids	2.54– 2.77	2.67	356	2.60– 2.77	2.66	287	2.52– 2.73	2.65	102
Porosity, undisturbed (percent)	26.0 – 53.3	43	243	28.5 – 48.9	39	127	30.9 – 46.4	39	26
Porosity, repacked (percent)	26.7 – 50.2	32	134	27.2 – 52.3	35	213	37.0 – 42.0	34	132
Centrifuge-moisture equivalent (percent)	.1 – 33.7	4	288	.1 – 8.8	1	295	.1 – 8.2	1	142
Specific retention (percent)	.3 – 43.2	8	264	.1 – 17.8	4	292	.5 – 17.6	5	143
Specific yield (percent)	1.0 – 45.9	33	287	16.2 – 46.2	32	297	18.4 – 42.9	30	143
Gravel									
Permeability, repacked (gpd per sq ft)	960 –66,000	11,000	22	730 –40,000	6,700	11	1,200 – 7,400	3,700	7
Dry unit weight (g per cc)	1.60– 1.99	1.76	41	1.47– 2.09	1.85	24	1.69– 2.08	1.93	15
Specific gravity of solids	2.63– 2.76	2.68	19	2.65– 2.79	2.71	25	2.64– 2.76	2.69	17
Porosity, repacked (percent)	25.1 – 38.5	34	38	23.7 – 44.1	32	22	23.8 – 36.5	28	15
Centrifuge-moisture equivalent (percent)	.01– 8.2	2	33	.1 – 6.8	3	15	.6 – 5.4	3	10
Specific retention (percent)	.06– 16.7	7	33	.6 – 14.9	7	13	3.1 – 13.8	9	10
Specific yield (percent)	12.6 – 39.9	28	33	16.9 – 43.5	24	13	13.2 – 25.2	21	9

TABLE 6.—*Properties of silt and clay*

Test	Silt			Clay		
	Range	Arithmetic mean	Number of analyses	Range	Arithmetic mean	Number of analyses
Permeability, vertical (gpd per sq ft) _____	0. 0002–15	0. 6	39	0. 00003– 0. 01	0. 002	19
Permeability, horizontal (gpd per sq ft) __	. 0004–23	2	39	. 0002 – . 03	. 005	19
Dry unit weight (g per cc) _____	1. 01 – 1. 79	1. 38	374	1. 18 – 1. 72	1. 49	91
Specific gravity of solids _____	2. 47 – 2. 79	2. 62	388	2. 51 – 2. 77	2. 67	104
Porosity, undisturbed (percent) _____	33. 9 –61. 1	46	281	34. 2 –56. 9	42	74
Porosity, repacked (percent) _____	41. 0 –56. 0	46	85	39. 9 –52. 8	48	16
Centrifuge-moisture equivalent (percent) _____	3. 6 –46. 5	13	266	15. 6 –51. 1	30	27
Specific retention (percent) _____	3. 2 –45. 0	28	266	24. 6 –46. 9	38	27
Specific yield (percent) _____	1. 1 –38. 6	20	266	1. 1 –17. 6	6	27
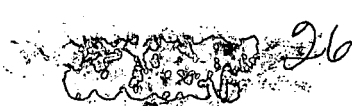
study, however, comparisons were made only on the basis of predominant particle size.

Analysis of individual sample data has indicated that horizontal permeabilities for the same sample are generally higher that the vertical permeabilities, and that repacked permeabilities are higher than either the horizontal or vertical permeabilities, which seems to be a logical relation—especially for stratified sedimentary rocks. Data also indicate that repacked porosity is generally higher than undisturbed porosity and that the dry unit weight of repacked samples is generally lower than that of undisturbed samples.

Silt and clay and their consolidated counterparts—siltstone, claystone, and shale—bear the same relation to one another that the coarse-grained rocks exhibit. Clay is the poorest source of water supply, not because it has low porosity and contains no water, but because the particles of clay and their interstices are very small. So, even though the porosity may be comparatively large, the minute pores hold water tenaciously and release it slowly.

WIND-LAID DEPOSITS

Wind-laid deposits are generally formed from the particles that are derived from weathering of older rocks and are transported by
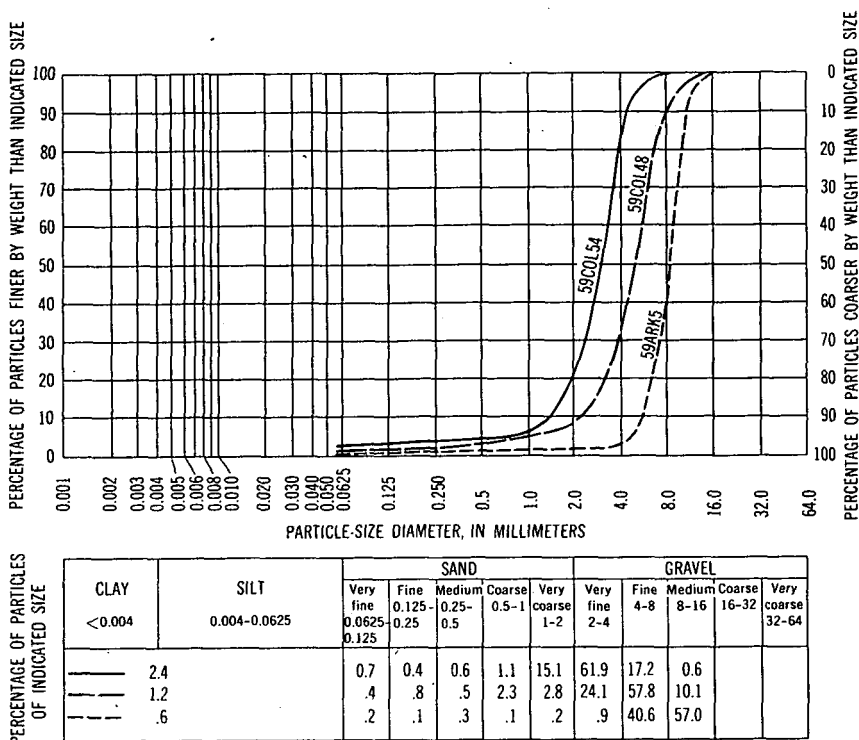
		SAND					GRAVEL				
CLAY	SILT	Very fine 0.0625-0.125	Fine 0.125-0.25	Medium 0.25-0.5	Coarse 0.5-1	Very coarse 1-2	Very fine 2-4	Fine 4-8	Medium 8-16	Coarse 16-32	Very coarse 32-64
<0.004	0.004-0.0625										
—— 2.4		0.7	0.4	0.6	1.1	15.1	61.9	17.2	0.6		
— — 1.2		.4	.8	.5	2.3	2.8	24.1	57.8	10.1		
– – – .6		.2	.1	.3	.1	.2	.9	40.6	57.0		

HYDROLOGIC AND PHYSICAL PROPERTIES

Lab. No.	Location	Depth of sample (feet)	Specific gravity of solids	Dry unit weight (g per cc)	Specific retention (percent of volume)	Total porosity (percent of volume)	Specific yield (percent of volume)	Coefficient of permeability (gpd per sq ft)
59COL54____	Arapahoe County, Colo_____	47.5–52.2	2.61	1.62	6.6	37.9	31.3	4,100
59COL48____	Douglas County, Colo_____	35.0–37.5	2.63	1.62	5.5	38.4	32.9	29,000
59ARK5_____	Arkansas River valley, Ark_____	85.0	2.63	1.47	.6	44.1	43.5	40,000

FIGURE 6.—Typical data on particle-size distribution and the hydrologic and physical properties of water-laid gravel.

wind to the site of deposition. Loess and eolian sand are good examples of these rocks. Tuff is also a wind-transported material, although it is a product not of weathering but of violent volcanic activity. The fine ash that is ejected into the atmosphere during the volcanic activity is carried by winds and subsequently deposited in beds.

Loess, eolian sand.—Loess is considered to be a nonstratified, generally unconsolidated deposit consisting of fine homogeneous
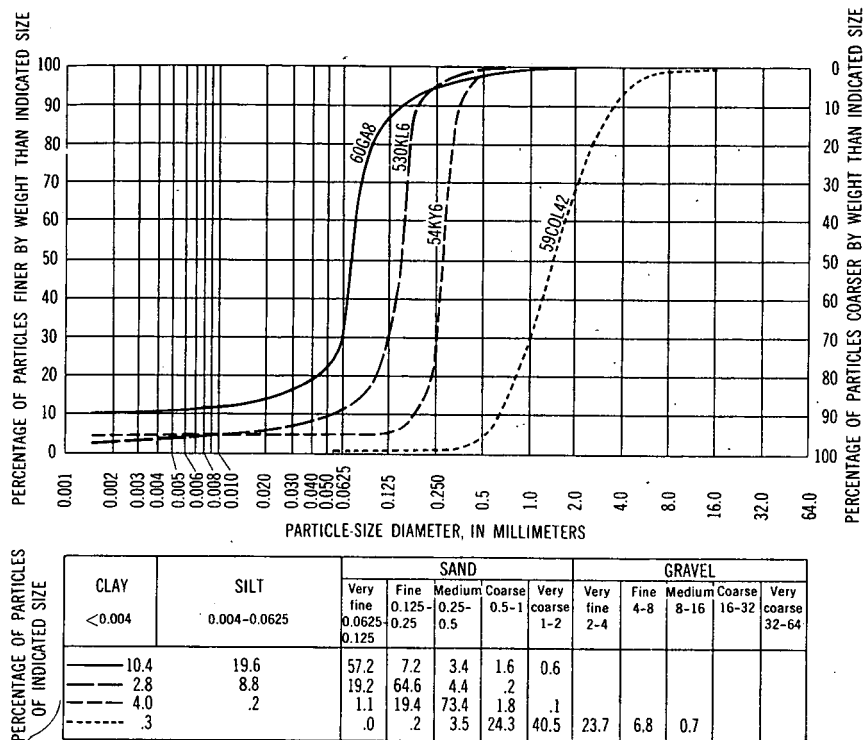
PERCENTAGE OF PARTICLES OF INDICATED SIZE	CLAY <0.004	SILT 0.004–0.0625	SAND					GRAVEL				
			Very fine 0.0625–0.125	Fine 0.125–0.25	Medium 0.25–0.5	Coarse 0.5–1	Very coarse 1–2	Very fine 2–4	Fine 4–8	Medium 8–16	Coarse 16–32	Very coarse 32–64
———	10.4	19.6	57.2	7.2	3.4	1.6	0.6					
— — —	2.8	8.8	19.2	64.6	4.4	.2						
– – –	4.0	.2	1.1	19.4	73.4	1.8	.1					
······	.3		.0	.2	3.5	24.3	40.5	23.7	6.8	0.7		

HYDROLOGIC AND PHYSICAL PROPERTIES

Lab. No.	Location	Depth of sample (feet)	Specific gravity of solids	Dry unit weight (g per cc)	Specific retention (percent of volume)	Total porosity (percent of volume)	Specific yield (percent of volume)	Coefficient of permeability (gpd per sq ft)
60GA8_____	Brunswick, Ga_____	496.0–497.0	2.71	1.58	22.8	41.7	18.9	13
530KL6___	McCurtain County, Okla____	_____	2.65	1.90	.7	28.3	27.6	79
54KY6____	Gallaway County, Ky_____	_____	2.67	1.48	1.0	44.6	43.6	400
59COL42__	Arapahoe County, Colo_____	33.5–34.0	2.61	1.67	2.9	36.0	33.1	6,000

FIGURE 7.—Typical data on particle-size distribution and the hydrologic and physical properties of water-laid sand.

buff-colored silt and some clay and fine sand. Loess consists chiefly of angular particles of silt-size quartz that is commonly cemented by calcareous cement and that weathers to vertical walls. Eolian sand also is deposited by wind, but it occurs most commonly as sand dunes. The material composing eolian sand is more rounded and coarser than that normally composing loess. Both deposits occur principally along uplands adjacent to rivers, lakes, or oceans.
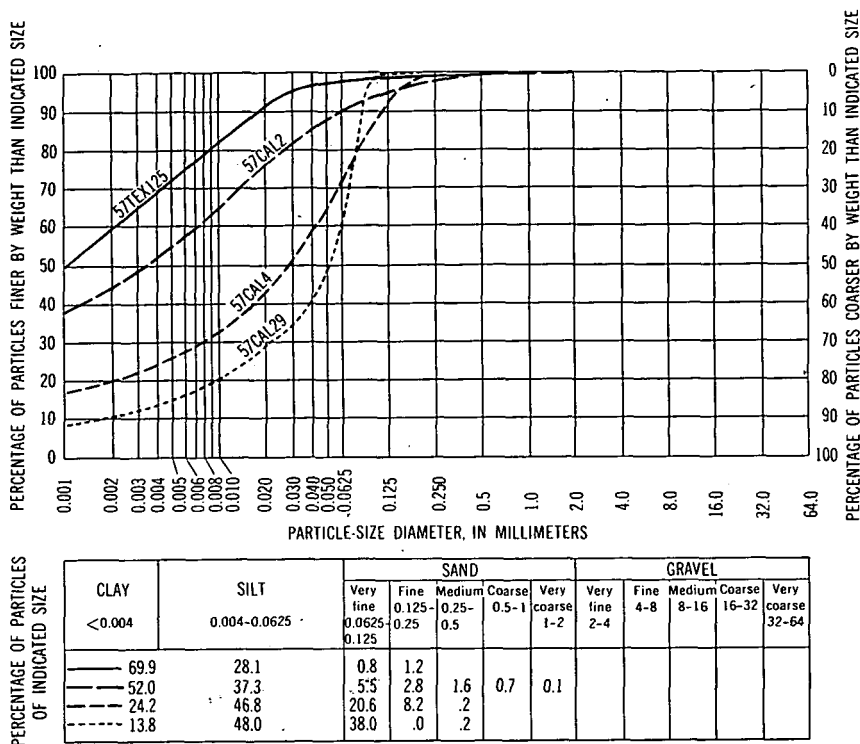
PERCENTAGE OF PARTICLES OF INDICATED SIZE	CLAY <0.004	SILT 0.004–0.0625	SAND					GRAVEL				
			Very fine 0.0625–0.125	Fine 0.125–0.25	Medium 0.25–0.5	Coarse 0.5–1	Very coarse 1–2	Very fine 2–4	Fine 4–8	Medium 8–16	Coarse 16–32	Very coarse 32–64
————	69.9	28.1	0.8	1.2								
— — —	52.0	37.3	.5	2.8	1.6	0.7	0.1					
— · — ·	24.2	46.8	20.6	8.2	.2							
- - - - -	13.8	48.0	38.0	.0	.2							

HYDROLOGIC AND PHYSICAL PROPERTIES

Lab. No.	Location	Depth of sample (feet)	Specific gravity of solids	Dry unit weight (g per cc)	Specific retention (percent of volume)	Total porosity (percent of volume)	Specific yield (percent of volume)	Coefficient of permeability (gpd per sq ft)
57TEX125___	Univ. Houston, Tex_____	800.5–801.0	2.61	1.64	37.2	37.2	0	0.00001
57CAL2_____	Mendota, Calif__	110.5–111.0	2.66	1.56	41.4	41.4	0	.01
57CAL4_____	___do_____	191.5–192.0	2.70	1.52	27.2	43.7	16.5	.2
57CAL29____	___do_____	773.0–773.5	2.75	1.57	22.9	42.9	20.0	2

FIGURE 8.—Typical data on particle-size distribution and the hydrologic and physical properties of water-laid silt and clay.

Table 7 summarizes the properties of these materials, and figures 9 and 10 present typical data on hydrologic and physical properties, as related to particle-size distribution.

Tuff.—Tuff is a fine-textured volcanic rock formed by the compaction of volcanic dust after it settles from the air. The formation of tuff is generally aided by the action of percolating water. Tuff is generally light in weight and color and is composed of angular particles of quartz, feldspar, and other minerals. Table 8 summarizes properties of tuff.

TABLE 7.—*Properties of loess and eolian sand*

Test	Loess			Eolian sand		
	Range	Arithmetic mean	Number of analyses	Range	Arithmetic mean	Number of analyses
Permeability, vertical (gpd per sq ft)	0. 1 – 4	2	6	22 –1, 500	500	6
Dry unit weight (g per cc)	1. 25– 1. 62	1. 45	18	1. 33– 1. 70	1. 58	15
Specific gravity of solids	2. 64– 2. 74	2. 67	36	2. 63– 2. 70	2. 66	13
Porosity, undisturbed (percent)	44. 0 –57. 2	49	5	39. 9 – 50. 7	45	6
Porosity, repacked (percent)	43. 0 –53. 0	46	6	36. 8 – 41. 5	38	9
Centrifuge-moisture equivalent (percent)	13. 2 –28. 7	22	13	. 1 – 1. 8	1	14
Specific retention (percent)	21. 8 –29. 8	27	5	. 5 – 5. 8	3	14
Specific yield (percent)	14. 1 –22. 0	18	5	32. 3 – 46. 7	38	14

TABLE 8.—*Properties of tuff*

Test	Range	Arithmetic mean	Number of analyses
Permeability, vertical (gpd per sq ft)	0. 0001–17	4	44
Permeability, horizontal (gpd per sq ft)	. 0001–17	5	44
Dry unit weight (g per cc)	1. 17 – 2. 31	1. 48	230
Specific gravity of solids	2. 30 – 2. 64	2. 50	174
Porosity, undisturbed (percent)	7. 2 –54. 7	41	180
Centrifuge-moisture equivalent (percent)	2. 5 –30. 0	13	76
Specific retention (percent)	5. 6 –38. 2	21	90
Specific yield (percent)	2. 0 –47. 0	21	90

Water-bearing properties of wind-laid deposits.—Most wind-blown materials are not very coarse. Fine material is generally blown from sites of aqueous deposition by the wind and deposited as dunes or sheets. The coarser deposits of sand therefore have irregular stratification and extreme irregularity of crossbedding and other structure, owing to the variability of wind direction and alternation of scouring and deposition. For any specific sand sample taken from one section of a dune, however, the degree of sorting is generally good. The hydrologic properties may therefore be somewhat different from those of water-laid sand of the same texture. The data here presented indicate that both porosity and permeability are somewhat higher for eolian sand than for water-laid material of the same particle size.
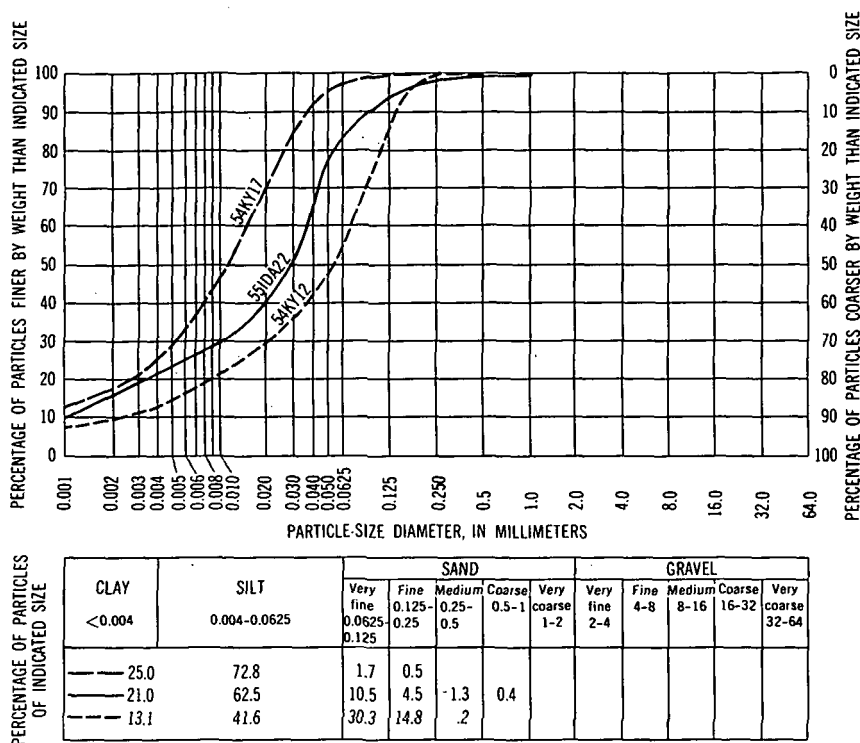
		SAND					GRAVEL				
CLAY <0.004	SILT 0.004-0.0625	Very fine 0.0625- 0.125	Fine 0.125- 0.25	Medium 0.25- 0.5	Coarse 0.5-1	Very coarse 1-2	Very fine 2-4	Fine 4-8	Medium 8-16	Coarse 16-32	Very coarse 32-64
———— 25.0	72.8	1.7	0.5								
———— 21.0	62.5	10.5	4.5	1.3	0.4						
———— 13.1	41.6	30.3	14.8	.2							

HYDROLOGIC AND PHYSICAL PROPERTIES

Lab. No.	Location	Depth of sample (feet)	Specific gravity of solids	Dry unit weight (g per cc)	Specific retention (percent of volume)	Total porosity (percent of volume)	Specific yield (percent of volume)	Coefficient of permea- bility (gpd per sq ft)
54KY17___	Henderson County, Ky_____	_____	2.74	1.54	29.7	43.8	14.1	0.02
55IDA22__	National Reactor Testing Station, Idaho_____	_____	2.73	1.53	_____	44.0	_____	1
54KY12____	Henderson County, Ky_____	_____	2.67	1.44	13.0	46.1	33.1	4

FIGURE 9.—Typical data on particle-size distribution and the hydrologic and physical properties of loess.

Silt transported by the wind may lack all stratification. Loess is loosely cemented and generally has interstices of such size that it has a high water-retention capacity and a low permeability.

Tuff may be sorted somewhat by water after deposition, but ordinarily the original deposits are loosely packed and poorly sorted. After consolidation, some tuff still exhibits—to a reduced degree— a high porosity. Because the heavier and coarser particles fall first, tuff particles grade generally from coarse at the bottom of the deposit
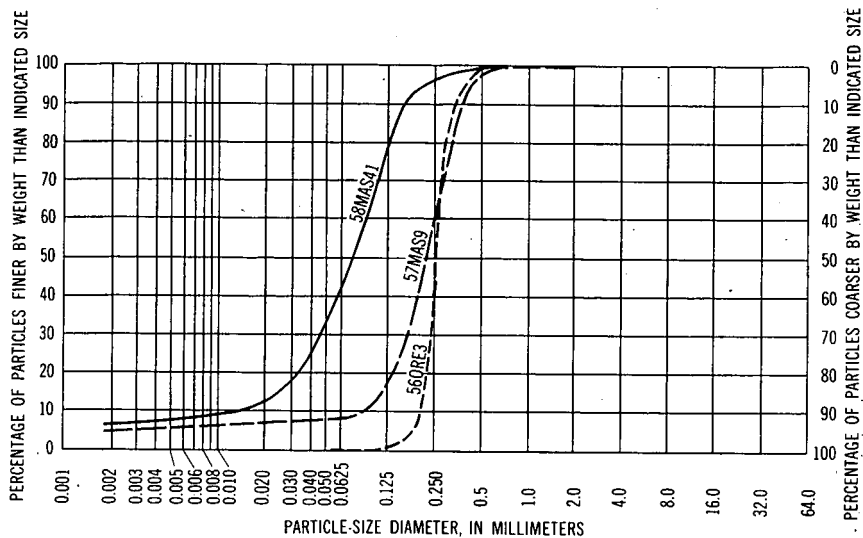
CLAY	SILT	SAND					GRAVEL				
		Very fine 0.0625-0.125	Fine 0.125-0.25	Medium 0.25-0.5	Coarse 0.5-1	Very coarse 1-2	Very fine 2-4	Fine 4-8	Medium 8-16	Coarse 16-32	Very coarse 32-64
<0.004	0.004-0.0625										
7.1	36.1	36.4	17.2	2.8	0.4						
5.3	2.5	10.0	51.8	28.4	2.0						
.1		.2	44.9	54.6	.1	0.1					

HYDROLOGIC AND PHYSICAL PROPERTIES

Lab No.	Location	Depth of sample (feet)	Specific gravity of solids	Dry unit weight (g per cc)	Specific retention (percent of volume)	Total porosity (percent of volume)	Specific yield (percent of volume)	Coefficient of permeability (gpd per sq ft)
58MAS41__	Ipswich River valley, Mass_____	2.0	2.70	1.33	4.0	50.7	46.7	22
57MAS9___	Middlesex County, Mass_____	2.5	2.68	1.61	1.0	39.9	38.9	250
56ORE3___	Florence, Oreg_____	_____	2.65	1.63	1.5	38.5	37.0	630

FIGURE 10.—Typical data on particle-size distribution and the hydrologic and physical properties of eolian sand.

to fine at the top. However, within the range of any one sample, the material can be considered to be fairly homogeneous. The data indicate a wide range of hydrologic and physical properties. One relation shown by the data indicates that porosity is fairly high, even though permeability is low.

ICE-LAID DEPOSITS

Rock debris transported by glacial ice and deposited either directly or in bodies of glacial melt water is called glacial drift. Drift

is separated into nonstratified drift (till) and stratified drift, sometimes referred to as washed drift.

Till and washed drift.—Because some melt water is associated with most glacial deposition, the dividing line between till and washed drift is not sharp. However, till is regarded in this report as being primarily unsorted drift, and washed drift is considered as being those deposits that have been sorted by the action of melt water.

Till is rock debris directly deposited by glacial ice and has a wide range of particle sizes. Till differs widely in composition and textures in different places. Most till contains considerable clay and is therefore sometimes called boulder clay.

Washed drift can be divided into two classes: proglacial drift— deposits made beyond the limits of the glacier (outwash)—and ice-contact deposits, which include eskers, kame terraces, kames, and features marked by numerous kettles. These two classes grade directly into each other, and for purposes of study, no distinction is made between the two.

Table 9 summarizes the properties of ice-laid deposits, and figures 11 and 12 illustrate the typical hydrologic and physical properties, as related to particle-size distribution, of such deposits.

Water-bearing properties of ice-laid deposits.—Glacial drift has a very wide range in size of materials, containing debris of all sizes from clay to boulders. The materials directly deposited by the ice are a heterogeneous mixture of these particles and are called till. Till differs greatly in composition in different places, depending on the source materials. Because it is unsorted, till generally has low porosity and permeability and is a poor producer of water, particularly if it is compact clay till. However, sandier till (though of lower porosity) is more permeable and in some places is a fair producer of water.

Washed drift contains sorted sand and gravel, generally intermingled and interbedded with till. Such deposits differ greatly (even in the same locality) in thickness, coarseness of material, depth, and areal extent, and rarely extend more than a few miles. Laboratory data indicate that the water-bearing properties of washed drift compare favorably with those of water-laid sand; that is, the washed drift has fairly high porosity and permeability, especially in comparison to clay till.

CHEMICAL AND ORGANIC ORIGIN

Chemical origin

Rocks of chemical origin are formed from mineral material that was in solution but became insoluble and precipitated. These deposits may form either by direct chemical precipitation in open bodies of water or by concentration and precipitation through

TABLE 9.—*Properties of till and washed drift*

[Classified according to predominant particle size]

Test	Clay Range	Clay Arithmetic mean	Clay Number of analyses	Silt Range	Silt Arithmetic mean	Silt Number of analyses	Sand Range	Sand Arithmetic mean	Sand Number of analyses	Gravel Range	Gravel Arithmetic mean	Gravel Number of analyses
Till												
Permeability, repacked (gpd per sq ft)							0.5 - 80	12	18	2 -2,600	730	8
Permeability, vertical (gpd per sq ft)	0.00008- 0.009	0.002	7	0.0003- 0.4	0.06	12	.06- 220	24	10			
Dry unit weight (g per cc)				1.61 - 1.91	1.78	15	1.69- 2.12	1.88	11	1.72- 2.12	1.91	4
Specific gravity of solids	2.61 - 2.69	2.65	8	2.64 - 2.77	2.70	15	2.63- 2.73	2.69	13	2.67- 2.78	2.72	8
Porosity, undisturbed (percent)				29.5 - 40.6	34	15	22.1 - 36.7	31	10			
Porosity, repacked (percent)										22.1 - 30.3	26	3
Centrifuge-moisture equivalent (percent)				11.7 - 21.2	15	11	.4 - 15	6	10	.1 - 17.4	7	4
Specific retention (percent)				22.6 - 33.4	28	11	2.5 - 28.8	14	10	.6 - 24.6	12	4
Specific yield (percent)				0.5 - 13.0	6	11	1.9 - 31.2	16	10	5.1 - 34.2	16	4
Washed drift												
Permeability, repacked (gpd per sq ft)				250 -3,750	940	13	500 -12,700	5,000	9			
Permeability, vertical (gpd per sq ft)	1 -12	5	5	24 -1,400	340	27						
Dry unit weight (g per cc)	1.11 - 1.66	1.38	5	1.36 - 1.83	1.55	36	1.47- 1.78	1.60	6			
Specific gravity of solids	2.70 -2.73	2.72	5	2.65 - 2.75	2.69	38	2.65- 2.75	2.68	8			
Porosity, undisturbed (percent)	38.4 -59.3	49	5	36.2 - 47.6	44	31	34.6 - 41.5	39	3			
Porosity, repacked (percent)				31.6 - 41.9	36	5	37.0 - 44.5	41	3			
Centrifuge-moisture equivalent (percent)	1.3 -10.3	5	5	.1 - 1.4	1	34						
Specific retention (percent)	4.7 -13.8	9	5	.5 - 5.7	3	35						
Specific yield (percent)	33.2 -48.1	40	5	29.0 - 48.2	41	35						

TABLE 10.—*Properties of limestone, dolomite, and peat*

Test	Limestone			Dolomite			Peat		
	Range	Arith-metic mean	Number of analyses	Range	Arith-metic mean	Number of analyses	Range	Arith-metic mean	Number of analyses
Permeability, vertical (gpd per sq ft)	0. 0003–160	23	28	0. 00008– 0. 07	0. 03	3	3 –280	140	2
Permeability, horizontal (gpd per sq ft)	. 0006–540	44	28						
Dry unit weight (g per cc)	1. 21 – 2. 69	1. 94	66	1. 83 – 2. 20	2. 02	2	0. 12– 0. 14	0. 13	4
Specific gravity of solids	2. 68 – 2. 88	2. 75	74	2. 64 – 2. 72	2. 69	3	1. 54	1. 54	4
Porosity, undisturbed (percent)	6. 6 – 55. 7	30	74	19. 1 –32. 7	26	2	92. 2	92	2
Centrifuge-moisture equivalent (percent)	. 7 – 17. 7	5	34				404. 3	404	2
Specific retention (percent)	4. 9 – 29. 1	13	32				48. 5	49	2
Specific yield (percent)	. 2 – 35. 8	14	32				43. 7	44	2

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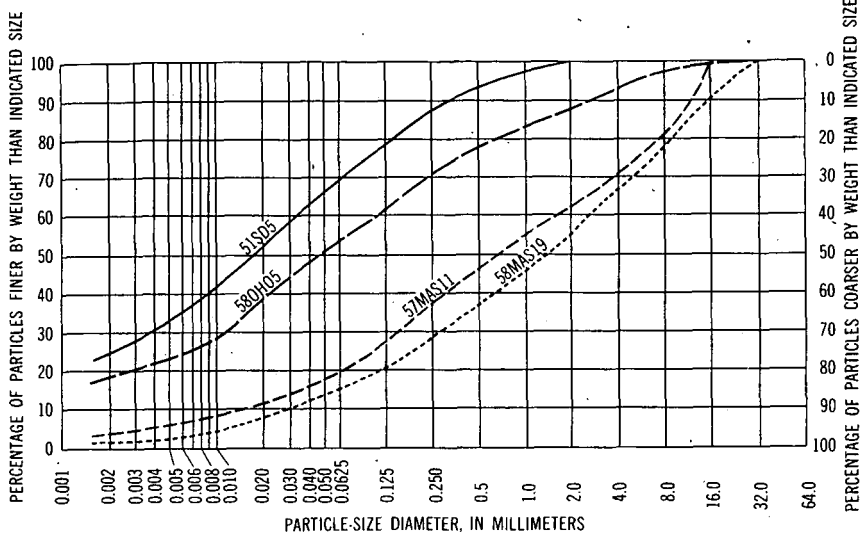
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			SAND					GRAVEL				
CLAY	SILT		Very fine	Fine	Medium	Coarse	Very coarse	Very fine	Fine	Medium	Coarse	Very coarse
<0.004	0.004-0.0625		0.0625-0.125	0.125-0.25	0.25-0.5	0.5-1	1-2	2-4	4-8	8-16	16-32	32-64
———— 30.5	38.9		9.0	8.8	6.2	3.8	2.8					
——— 21.9	31.7		7.7	9.1	7.4	5.3	4.7	4.9	4.5	2.2	0.6	
— — — 5.4	14.6		6.8	9.3	9.0	8.7	8.0	9.2	10.5	18.5		
-------- 2.1	12.8		5.1	7.6	8.9	9.3	9.2	12.0	10.1	13.1	9.8	

HYDROLOGIC AND PHYSICAL PROPERTIES

Lab. No.	Location	Depth of sample (feet)	Specific gravity of solids	Dry unit weight (g per cc)	Specific retention (percent of volume)	Total porosity (percent of volume)	Specific yield (percent of volume)	Coefficient of permeability (gpd per sq ft)
51SD5_____	Hand County, S. Dak_____	97.0– 98.0	2.69	1.62	33.4	39.8	6.4	0.1
58OHO5___	Montgomery County, Ohio_____	_____	2.71	1.78	_____	33.9	_____	.08
57MAS11__	Middlesex County, Mass_____	2.5	2.72	2.12	2.5	22.1	19.6	2
58MAS19__	Brockton, Mass_____	_____	2.73	1.78	.6	34.8	34.2	97

FIGURE 11.—Typical data on particle-size distribution and the hydrologic and physical properties of till.

evaporation in isolated bodies of water. One rock of chemical origin is chert. Although some tests have been made on chert in the laboratory, data are not complete enough to be presented in this report.

Organic origin

Rocks of organic origin may form in many different ways. They may form from precipitation or accumulation of calcium carbonate from water by organisms, or they may form from accumulations of

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	CLAY	SILT	SAND					GRAVEL				
			Very fine 0.0625-0.125	Fine 0.125-0.25	Medium 0.25-0.5	Coarse 0.5-1	Very coarse 1-2	Very fine 2-4	Fine 4-8	Medium 8-16	Coarse 16-32	Very coarse 32-64
	<0.004	0.004-0.0625										
————	7.6	89.0	3.2	0.2								
—— — —	3.8	9.4	46.0	39.6	1.2							
— — — —	1.2	.0	.4	6.3	46.3	32.1	11.8	1.6	0.3			
--------	6.3	4.0	1.0	2.1	2.3	4.2	7.2	15.4	25.3	22.5	9.7	

HYDROLOGIC AND PHYSICAL PROPERTIES

Lab. No.	Location	Depth of sample (feet)	Specific gravity of solids	Dry unit weight (g per cc)	Specific retention (percent of volume)	Total porosity (percent of volume)	Specific yield (percent of volume)	Coefficient of permea- bility (gpd per sq ft)
57MAS17__	Middlesex County, Mass_____	15	2.72	1.12	13.3	58.8	45.5	
58MAS36__	Ipswich River valley, Mass_____	2	2.69	1.41	2.8	47.6	44.8	71
58MAS44__	____do_____	2	2.67	1.47	.9	44.9	44.0	1,400
59MCH2__	Kalamazoo, Mich_____	1-2	2.72	1.78	26.5	34.6	8.1	130

FIGURE 12.—Typical data on particle-size distribution and the hydrologic and physical properties of washed drift.

plant and (or) animal life, which decays and produces carbonaceous materials. Limestone, dolomite, and peat are the only materials of organic origin considered in this report.

Limestone, dolomite, and peat.—Limestone is a common and widely distributed calcium carbonate rock. It is fine grained and generally gray and will effervesce freely when tested with cold dilute hydro-chloric acid. Dolomite differs from limestone in that it contains magnesium and will effervesce only slightly when tested with cold

hydrochloric acid. Peat is a soft, dark-brown to black deposit produced by the partial decomposition of plant and animal life under aqueous conditions. Table 10 summarizes the properties of materials of organic origin. Only a limited number of samples of peat and dolomite have been tested to date.

Water-bearing properties of rocks of chemical and organic origin.— No rocks differ more radically in their water-bearing character than do those of chemical and organic origin. Limestones and dolomites are generally dense and massive, and their ability to carry and yield water is dependent not on their original texture but on secondary structures such as fractures, solution cavities, and joints, all of which exist or are produced or enlarged by the solvent action of water.

Limestone and dolomite may, when newly formed, contain many interstices. However, during compaction or as the calcareous materials are dissolved and again precipitated, these pores are filled. Accordingly, older limestone is generally compact, and the passages for water storage and transport form along fractures, joints, and bedding planes, or by solution, mostly along bedding planes and joints. If limestone or dolomite that originally occupied a position where water actively circulated was subsequently moved below the water table, a good water-bearing formation resulted. Dolomite, however, differs from limestone in that it is somewhat less soluble than limestone. The hydrologic properties determined for limestone and dolomite in the laboratory generally indicate the properties of the original structure of the rock, and they are consequently very low.

Peat, because of its fibrous nature, is extremely absorbent and has a high water-retention capacity. Peat has a very high porosity but despite this has poor water-producing characteristics.

METAMORPHIC ROCKS

Metamorphic rocks are those that have been so changed—usually in the presence of liquids or gases—by heat and pressure that rocks having new characteristics are formed. The change occurs in either the mineral composition or the texture, or in both. Only a few representatives of this rock class have been analyzed in the Hydrologic Laboratory.

Slate and schist.—Slate is a very fine textured rock resulting mainly from the deep-seated deformation of clay and shale. The cleaved surfaces tend to be very smooth because of the fineness of the mineral grains. Schist is a crystalline rock with a secondary foliation, but it is somewhat coarser grained than slate. It commonly splits along the foliation to form irregular plates. Mica schist—the common type— results from the recrystallization of sandstone, shale, or clay, or from the excessive shearing of granitoid and porphyritic igneous rocks.

Table 11 summarizes the properties for slate and schist. The highest permeabilities, porosities, and specific yields, and lowest specific retentions were obtained for samples of weathered schist.

TABLE 11.—*Properties of slate and schist*

Test	Slate			Schist		
	Range	Arith-metic mean	Number of analyses	Range	Arith-metic mean	Number of analyses
Permeability, vertical (gpd per sq ft)	·0. 003004–0. 001	0. 0002	8	0. 00004 –24	4	17
Dry unit weight (g per cc)				1. 42 – 2. 69	1. 76	21
Specific gravity of solids	2. 85 –3. 05	2. 94	10	2. 70 – 2. 84	2. 79	21
Porosity, undisturbed (percent)				4. 4 –49. 3	38	18
Centrifuge-moisture equivalent (percent)				4. 5 –15. 8	10	12
Specific retention (percent)				10. 3 –23. 6	17	11
Specific yield (percent)				21. 9 –33. 2	26	11

Quartzite.—Quartzite is a compact rock composed of interlocking quartz grains. It is formed by the metamorphism of sandstone and is distinguished from sandstone by the fact that fractures in quartzite pass through the grains of quartz, producing an uneven surface. Data on the properties of quartzite are not available in the laboratory at present.

Water-Bearing Properties of Metamorphic Rocks.—Metamorphic rocks are generally dense and compact, and the storage and transport of water occurs mainly in fractures, joints, cleavage planes, and solution passages. Some weathered rocks of this class contain water at their surfaces, although they do not readily yield water because of their fine texture. The more crystalline rocks of this class are similar in their water-bearing properties to the crystalline igneous rocks. Schist, for example, carries water in small openings that form parallel to the planes of foliation, but horizontal joint patterns, which are prevalent in granite, are scarce. Slate, schist, quartzite, and marble have low porosity and permeability when tested in their sedimentary form. However, slate yields water through joints and cleavage planes; quartzite, through joints; and marble, along bedding or joint planes or through solution passages formed along them. The results of physical and hydrologic analyses obtained in the laboratory pertain to the matrix of the rock and not to the secondary structures.

SUMMARY

Laboratory data presented in this report should be used with caution. Use depends greatly on the source and range of the data and on the number of samples or analyses upon which results or conclusions are based. The larger the sampling population, the more meaningful

and useful the data. To allow the reader to assess the reliability of the data in this report, the physical and hydrologic data have been tabulated for each rock type, and both the number of samples and the range of the data are given. Furthermore, for comparative use, the arithmetic mean has been calculated for each of the same groups.

Arkin, Herbert, and Colton (1956, p. 17) stated that the arithmetic mean is the most commonly used, most easily understood, and most generally recognized average; that its computation is relatively simple; and that it may be treated algebraically. They also pointed out, however, that the arithmetic mean may be greatly distorted by extreme values and therefore may not be typical. Nonetheless, the arithmetic mean was used in this report because of the ease of computation and because of the wide variety of uses to which it can be applied.

In addition to the detailed data presented in tables for individual rock types, the arithmetic means are summarized in one comprehensive table from which the relation of the rocks to one another can be studied (table 12). Again, caution should be used in relating data on one type of rock or test to that on another. For example, the reader might assume that both the repacked permeability and the undisturbed vertical permeability were determined for the same sample. This would be incorrect. For medium sand, as example, the data indicate only that the repacked permeability of 255 samples averaged about 300, and that the vertical permeability of 112 samples averaged about 340. Similarly, data on a particular grain size of sandstone cannot be compared directly to that of an unconsolidated sand of the same size. To do this, one would have to assume that the samples were comparable except for cementation, and this assumption would be incorrect. The data were obtained for samples taken from the rock matrix, and properties are not necessarily representative of the entire geologic formation.

Ordinarily, the arithmetic mean could be used in the field to describe rock for which a laboratory analysis is not available. Ideally, the field man should have some idea of the reliability of the value applied to the rock in question. Figure 13 graphically illustrates the distribution of repacked permeabilities for medium-sand samples. About 76 percent of the samples tested fall within the permeability class of 100–1,000 gpd per sq ft (gallons per day per square foot). The arithmetic mean of permeability for these samples was found to be about 300 gpd per sq ft. However, when the distribution of values for a particular property (as shown in figure 13) are known, the field man is still unable to definitely use any particular value from the graph for his rock because that particular rock could have a value at either extreme of the full range of values.

TABLE 12.—*Summary of the arithmetic mean of properties for all rock types*

[Classified according to predominant particle size]

Test	Sedimentary rocks															
	Water-laid deposits													Wind-laid deposits		
	Sandstone		Silt-stone	Clay-stone	Shale	Clay	Silt	Sand			Gravel			Loess	Eolian sand	Tuff
	Fine	Medium						Fine	Medium	Coarse	Fine	Medium	Coarse			
Permeability, repacked (gpd per sq ft)	--------	--------	--------	--------	--------	--------	--------	61	300	1,100	11,000	6,700	3,700	--------	--------	--------
Permeability, vertical (gpd per sq ft)	5	77	0.004	0.002	--------	0.002	0.6	94	340	680	--------	--------	--------	2	500	4
Permeability, horizontal (gpd per sq ft)	7	--------	--------	--------	--------	.005	2	--------	--------	--------	--------	--------	--------	--------	--------	5
Dry unit weight (g per cc)	1.76	1.68	1.61	1.51	2.53	1.49	1.38	1.55	1.69	1.73	1.76	1.85	1.93	1.45	1.58	1.48
Specific gravity of solids	2.65	2.66	2.65	2.66	2.69	2.67	2.62	2.67	2.66	2.65	2.68	2.71	2.69	2.67	2.66	2.50
Porosity, undisturbed (percent)	33	37	35	43	6	42	46	43	39	39	--------	--------	--------	49	45	41
Porosity, repacked (percent)	--------	--------	43	--------	--------	48	46	32	35	34	34	31.9	28.3	46	38	--------
Centrifuge-moisture equivalent (percent)	6	4	14	--------	--------	30	13	4	1	1	2	3	3	22	1	13
Specific retention (percent)	13	10	29	--------	--------	38	28	8	4	5	7	7	9	27	3	21
Specific yield (percent)	21	27	12	--------	--------	6	20	33	32	30	28	24	21	18	38	21

| Test	Sedimentary rocks—Continued										Igneous rocks			Metamorphic rocks	
	Ice-laid deposits							Chemical and organic deposits			Weathered granite	Weathered gabbro	Basalt	Schist	Slate
	Till				Washed drift			Limestone	Dolomite	Peat					
	Clay	Silt	Sand	Gravel	Silt	Sand	Gravel								
Permeability, repacked (gpd per sq ft)			12	730		940	5,000								
Permeability, vertical (gpd per sq ft)	0.002	0.06	24		5	340		23	0.03	140	35	4	0.2	4	0.0002
Permeability, horizontal (gpd per sq ft)								44							
Dry unit weight (g per cc)		1.78	1.88	1.91	1.38	1.55	1.60	1.94	2.02	.13	1.50	1.73	2.53	1.76	
Specific gravity of solids	2.65	2.70	2.69	2.72	2.72	2.69	2.68	2.75	2.69	1.54	2.74	3.02	3.07	2.79	2.79
Porosity, undisturbed (percent)		34	31		49	44	39	30	26	92	45	43	17	38	
Porosity, repacked (percent)				26		36	41								
Centrifuge-moisture equivalent (percent)		15	6	7	5	1		5		404				10	
Specific retention (percent)		28	14	12	9	3		13		49				17	
Specific yield (percent)		6	16	16	40	41		14		44				26	
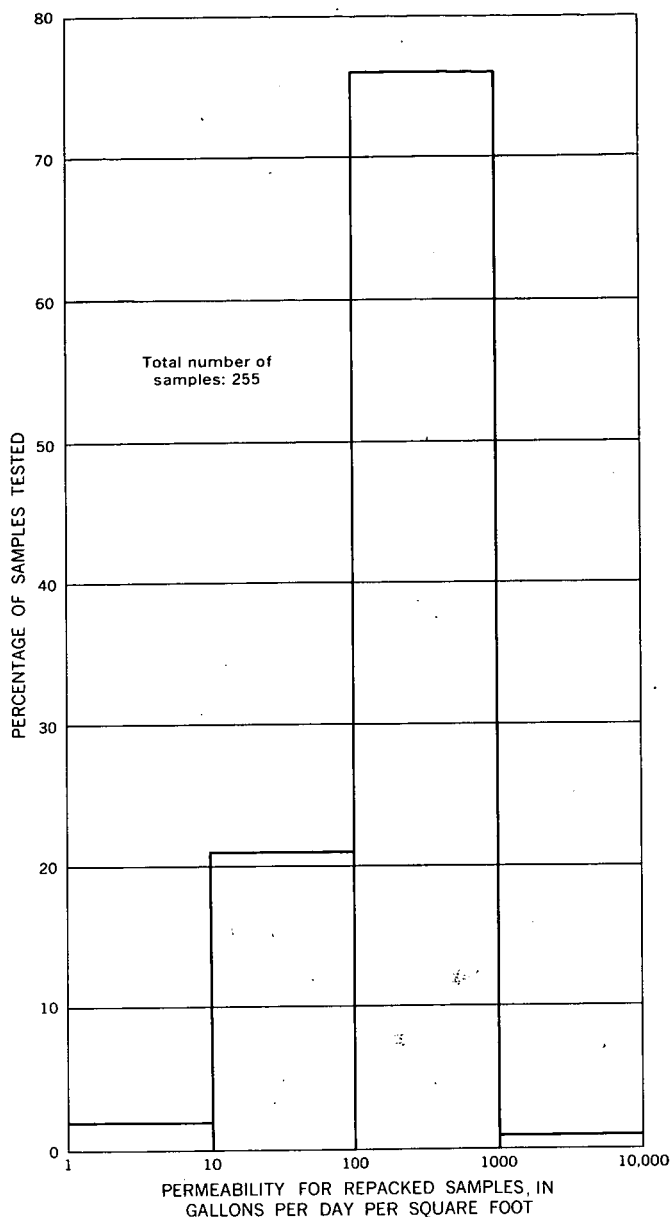
FIGURE 13.—Distribution of permeability for repacked samples of water-laid medium sand.

Because a hydrologic or physical property of a rock in the field may fall at the extreme limits of the range of values, precise data for various properties must depend upon laboratory analysis of a

sample. If only comparative values for a particular property are required and laboratory testing is not possible, the data contained in the tables of this report should be useful in the analysis of many engineering and geologic problems.

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